Disablement of a Surgical Drill via CT Guidance to Protect Vital Anatomy

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ABSTRACT

Applying image-guidance to an electronically-controlled surgical drill can prevent damage to patients’ anatomy during resection. A system is presented that disables the drill when it nears pre-defined critical patient anatomy. The system consists of a tracking system, image-guidance software, and drill-control circuit. The software was developed in C++ with the help of the Image-Guided Surgery Toolkit, and was designed to track tools based on input from a MicronTracker® (Claron Tech, Toronto, Ontario) tracking system. The system registers physical to image space using fiducial markers rigidly attached to the patient, tracks the drill, and automatically disables the drill when close to restricted regions. A coordinate reference frame is used for all physical acquisitions. Visual feedback of the tool’s position in image space is provided during tracking. Two tests were performed to determine the feasibility of the system. Virtual restricted regions were defined inside a phantom, and an operator attempted to drill the phantom with the help of the application. No feedback was provided to the user except for the automatic disablement of the drill by the application when close to a restricted region. In the first test, the drill was disabled at 0.74 ± 0.46 mm from the restricted region and entered 5.3% of the surface area of the restricted region. In the second test, the drill was disabled 1.3 ± 0.69 mm from the restricted region and entered the restricted region 8.5% of the time. We conclude that the system shows promise and further testing should be conducted.

Keywords: Image guidance, tracking, automatic control, drill disablement

1. INTRODUCTION

One of the common applications of image-guidance systems (IGS) is to provide a visual feedback of the current location of a surgical tool relative to the anatomy in the pre-operative images. While drilling, the surgeon refers frequently to this updated display to verify the region of operation and the underlying anatomical structures that are not yet visible to the eye, but can be identified in the pre-operative images. The idea is to prevent any injury to critical anatomical structures during the procedure. While looking at the display, if there is any unexpected movement of the surgical drill, which runs usually at 80000 rpm, then there is a possibility of injury to critical structures. Hence good hand-eye coordination is expected from the surgeon. It will be helpful to have a control system that automatically shuts off the drill as its tip nears critical structures. It will provide added safety controls that benefit both the patient and the surgeon. We developed a system that tracks the position of the surgical drill and controls the power to the drill based on its corresponding position in the pre-operative image. When the drill approaches any of the pre-defined boundaries of vital structures, the system automatically shuts off the drill.

The disablement of drill is ideal for mastoidectomy surgery where bone behind the ear is ablated in close proximity to vital anatomy during the procedure. While there are over 100,000 mastoidectomies performed per year, image-guided systems are not prevalent in the fields of otology and neuro-otology\textsuperscript{[1]}. There are many critical structures present in the surgical field, such as the facial nerve, horizontal semi-circular canal, and the sigmoid sinus. While injury to these
structures is fairly rare (<1% of mastoidectomies result in facial nerve palsy[^2]), the results from damaging them can be quite severe. For example, injury to the facial nerve results in paralysis of the ipsilateral face causing facial droop, inability to protect the eye via the blink reflex, and inability to seal the mouth during eating.

During mastoidectomy, the surgeon must avoid contacting the facial nerve with the drill. The location of the nerve just below the bony surface is not obvious visually, but it is clearly visible in a pre-operative CT image volume. Thus, the three-dimensional surface of the nerve can be determined pre-operatively in the CT. During drilling, when the drill tip approaches that surface, the power to the drill is automatically removed under computer control, thereby disabling it and protecting the nerve. While image-guided systems in this area are rare, Strauss and colleagues recently released a feasibility study on the possible use of a similar drill-control system[^3]. In this paper, we present the system we designed to implement this drill-control.

### 2. DRILL-DISABLEMENT SYSTEM

The system consists of both hardware and software. The hardware consists of a surgical drill system, a drill-controller, a tracking system, and a computer. The software is a customized IGS installed in the computer.

#### 2.1 Hardware

**Surgical Drill System**: We use the eMax 2 High Performance Instrument System (The Anspach Effort, Inc., Palm Beach Gardens, FL) in our study. The system consists of a surgical drill, console unit that provides power supply for the drill, and a foot pedal for speed control.

**Drill-Controller**: We designed an external controller circuit that enables or disables the power input to the console of the drill system. The controller gets input from the computer through a parallel port communication and from the foot pedal of the drill system through a push-pull connector. It sends output to the surgical drill through another push-pull connector. It enables the power to the drill when the IGS in the computer system sends a high signal and the foot pedal is pressed. It disables the power to the drill if the computer sends a low signal or foot pedal is not pressed.

**Tracking System**: We use a MicronTracker 2, S60 model (Claron Technology Inc., Toronto, Ontario, Canada,) for tracking. It is a third-generation optical pose tracker[^4] meaning that it is totally passive and uses available light to observe objects stereoscopically. The tracker uses high-contrast interlocking geometric patterns, which can be printed on a laser jet printer, as markers. For example, Figure 1 shows three markers attached to the drill for tracking.

**Computer**: A 1.7GHz Pentium 4 machine with 1GB RAM and Windows XP operating system is used for this work. The IGS software was installed on this computer. The computer communicates with the tracking system through a firewire connection and with the controller through a parallel port connection. It receives input from the tracking system to identify the current location of the drill. Depending on the output of the software, the computer sends signals to the controller.

#### 2.1 Software

The custom image-guidance application loads a DICOM image volume and information of location of critical structures in the form of distance maps, interfaces with the MicronTracker, calibrates tools, registers the physical space to image space, tracks the drill, provides feedback to the user, and sends appropriate signals through the parallel port to enable or disable the drill depending on the location of the drill-tip. The output of the program is interpreted by the drill-control circuit, which controls the power to the surgical drill to enable or disable it.
The software intended to be simple, robust, and as error-proof as possible. In order to maximize these characteristics, the application was designed as a state machine. This approach requires that a system exist in one of a well-defined set of application states, with defined transitions into and out of each state. The state machine methodology is intended to prevent the application from entering into an unknown state and potentially encountering runtime errors.

The software is written in C++ with the help of the Image-Guided Surgery Toolkit (IGSTK)\(^5\) to run under the Microsoft Windows operating system. IGSTK is a free and open-source C++ library based on the Insight Segmentation and Registration Toolkit (ITK)\(^6\) and the Visualization Toolkit (VTK)\(^7\). ITK is a free and open-source library that implements segmentation and registration algorithms for volumes. VTK is also free and open-source, and is used for visualization, three-dimensional graphics, and image processing. The IGSTK library utilizes select methods from these libraries in order to create a framework that allows for rapid development and testing of image-guided surgery applications. All these libraries are cross-platform and are widely utilized. The move to IGSTK provided (a) platform-independence, (b) increased speed and reliability, and (c) faster development time. Platform independence was achieved through the use of both IGSTK for program development and the Fast Light Toolkit (FLTK) for GUI development\(^8\). FLTK is also free and open-source, and is a cross-platform C++ library.

2.1.1 Display

A graphical user interface (GUI) is important for any application especially for mission-critical applications. In an effort to reduce the complexity and maximize the performance, the GUI for this application was set simple with all the relevant information provided to the user at different states. Figure 2 shows a screenshot of the application after a CT scan was loaded. Three different two-dimensional views of the image—axial, coronal, and sagittal—and a three-dimensional view are provided to the user. The user can browse through the slices and rotate the three-dimensional view for inspection. During tracking, the display is updated showing the location of the tool tip.

The right side of the screen consists of various buttons for performing different operations like calibrating tools, loading pre-defined boundaries, performing physical-to-image registration, enabling tracking, enabling the drill disablement system, and troubleshooting. The buttons are activated and deactivated at the relevant portions of the application to enforce the state machine aspect of the programming.

Indicators are located at the bottom-right of the screen to indicate the visible markers and the status of the drill. The oval

![Figure 2: A screenshot of the application.](image-url)
indicator at the bottom right gives visual feedback on whether the application enabled (indicator goes green) or disabled (indicator goes red) the drill. Square indicators are used to indicate the visibility of the markers. The number of indicators depends on the tool being used. Each indicator turns to green if the corresponding marker is visible to the tracking system and to red when it is not. When a pre-set number of markers on the drill are not visible, the drill will be disabled by the application because it is not possible to determine the location of the drill-tip in the physical space. This visual feedback can be useful to determine the reason for the disablement of the drill. If drill is disabled and some of the marker indicators are red, then the drill could be enabled back by holding the drill in such a way that all the markers are seen by the tracking system. Instead, if the drill is disabled and all the markers are shown to be visible (like in Figure 2), then it implies that the drill approached a vital structure.

2.1.2 Registration and Tracking

Before we could track the movement of surgical drill, we need to register the image and physical space. The software provides facility to perform point-based rigid-body registration. Fiducial points for the registration could be picked from the CT image using the application or loaded as a list of points from a text file. The physical points are acquired using a calibrated probe. The software has the capability to calibrate tools like probe and drill that have markers attached. Once the physical points corresponding to the image points are acquired, point-based rigid-body registration is performed.[9]

We use for our study a fiducial frame that was developed by our group for image-guided otologic surgery.[10][11]. The fiducial frame consists of twelve fiducial markers and can be attached rigidly to a patient via a customized dental bite-block. The fiducial markers are titanium spheres that can be localized both in the CT and physical space.

A coordinate reference frame (CRF), which consists of a set of markers, is used during the physical acquisition. The fiducial marker locations are acquired relative to the CRF. After registration, the CRF is rigidly attached to the patient and the tools are acquired relative to the CRF. The use of CRF allows patient movement relative to the tracking system during the procedure.

2.1.3 Disablement

While tracking the location of the surgical drill encompasses most of the computational time of the application, the effort is useless if there is no methodology to disable the surgical drill when its tip approaches close to a restricted volume. In order to provide high accuracy, the restricted volume is determined using a distance map. The distance map is provided as input to the application. It is obtained from a different application that segments the vital structures in a CT image and creates a distance map file for each structure. A distance map file is a three-dimensional array providing the smallest distance, in millimeters, of the center of the voxel to the vital structure. Linear interpolation is used to compute the distance values at sub-voxel levels during tracking.

At a given time instant during tracking, the current physical location of the drill is transformed to the CT image space. The distance values corresponding to that transformed location are obtained from the distance map files. If all of these values are greater than the radius of the drill burr (which is input by the user during calibration), the point is determined to be outside of the restricted region and a high signal is sent to the controller to enable the drill. If any of these values is negative or zero, then the drill is considered to be inside a restricted region. The precision of the MicronTracker tracking system is documented as 0.25 mm[4]. Thus, as a safety measure an extra 0.25 mm buffer is added to the radius of the burr. If the distance value minus the drill burr radius minus this buffer is less than or equal to zero, then a low signal is sent to the controller to disable the drill. The low signal is also sent if the current location of the drill tip can not be determined accurately because some markers are not visible to the tracking system.

3. VALIDATION

For testing purpose, we utilized a piece of balsa wood as the phantom. Balsa was deemed soft enough to be drilled away easily, but could be seen on a CT image. Two experiments were designed for our validation study.
Experiment 1: A restricted region was defined as a simple rectangular prism that was similar to the block, but smaller in size and completely inside the block. A slice through the distance map is shown in Figure 3. This experiment was designed to test the use of the drill disablement system—drill a desired region without damaging any part of the restricted region.

Experiment 2: This experiment was designed to determine the accuracy of the system. CRF plays a major role in tracking. It is known that the use of CRF introduces error in the system [12]. The accuracy of tracking tends to decrease with increase in distance from the CRF. This experiment was, hence, designed to measure the performance of the drill disablement system as a function of distance from the CRF. A restricted region with three rectangular prisms was defined. The prisms were parallel to the CRF with varying distance from the CRF. A slice through the distance map of this restricted region is shown in Figure 4.

The fiducial frame was attached to the block of balsa wood (Figure 5(a)), and a CT scan was acquired. The CT scan and the distance map file for the experiment were loaded in the IGS system. The fiducial markers in the CT image were localized using different software (VU Planner, Vanderbilt University, Nashville, TN 2007) and loaded on to the IGS system. To acquire the physical locations of the markers the frame was first attached to a sturdy stand as shown in Figure 5(b). The physical locations of all the markers were acquired using a calibrated probe. Since the CRF was not attached to the frame during this acquisition, we were careful not to move the frame, stand, and the tracking system. The frame was removed from the stand and the CRF was attached (Figure 5(c)) without moving the stand and the tracking system. The stand was designed such that the frame and the CRF attach the same way to the stand. The locations of markers in the CRF were acquired, after which we know the location of all the fiducial markers relative to the CRF. The CRF is then attached to the block of balsa wood the same way the frame was attached (Figure 5(d)). Registration between the image and physical space was performed using the marker locations.

Virtual restricted region was defined for the experiment and the corresponding distance map files were saved using a MATLAB (The Mathworks, Natick, MA) program. The distance map file was loaded in the IGS system, and the drill disablement system was enabled. An operator then drilled the block with the power to the drill controlled by our system. A CRF was attached to the block of balsa wood to allow the phantom and the tracker to move during drilling. The position of the drill tip was continually tracked and updated in the CT space. No visual feedback of the restricted region was available to the user due to its virtual nature. Hence, the only way to avoid striking the restricted regions was through the use of the drill disablement system. The distance map files are consulted to determine the distance of the current location of the drill tip to the restricted region. The drill was disabled if (a) any of the markers on the CRF are not seen by the tracker, (b) fewer than desired set of markers on the drill are seen by the tracker, or (c) the distance of the current location of the drill tip to the restricted region is found to be less than the drill burr radius plus 0.25 mm buffer.

To quantify the performance of the drill disablement system, another CT scan of the balsa wood block with the fiducial frame attached was acquired after drilling.
4. RESULTS AND DISCUSSION

For the first experiment, a rectangular prism was defined within the wood. The wood was ablated in order to expose one surface of the prism. No feedback was provided to the user besides the drill disablement. A CT scan of the block of balsa wood after drilling was subsequently obtained. From this CT, the signed distance from the edge of the ablated portion of the wood to the restricted region was measured to determine the accuracy of the system, where a negative value means that the drill went inside the restricted region. For this measurement, the CT of the drilled balsa wood was registered with the original CT using the markers on the fiducial frame. For each voxel on the surface of the restricted region, the distance map value for the closest voxel with the intensity of air is determined. A depiction of these distances can be seen in Figure 6, while Table 1 displays the descriptive statistics about these distances. The drill was disabled an average of 0.74 ± 0.46 mm from the edge of the restricted region, and the drill...
Table 1. Statistics on distance (mm) from the restricted region when the drill was disabled.

<table>
<thead>
<tr>
<th>Index</th>
<th>Mean Distance</th>
<th>Maximum Distance</th>
<th>Min Distance</th>
<th>Median Distance</th>
<th>25th Percentile</th>
<th>75th Percentile</th>
<th>Standard Deviation</th>
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<tr>
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<td>0.38</td>
<td>1.44</td>
<td>1.67</td>
</tr>
</tbody>
</table>

A second experiment was performed to determine any dependency of the accuracy of the system on distance from the CRF. Three virtual rectangular restricted prisms were defined at varying distances from the CRF. A regular grid of holes was drilled into the balsa wood towards these restricted regions. The holes were drilled until the drill disablement system prevented the drill from advancing any further. Table 2 displays the distance from these holes to the restricted region after drilling was completed. Each table entry represents the shortest distance from a particular hole to the restricted region, and a blank cell represents a hole that never encountered the restricted region. Each column is parallel to the CRF. The average distance from a hole to the restricted region was 1.3 ± 0.69 mm, with a standard error of the mean of 0.11 mm. We do not see an obvious degradation in the accuracy with increase in the distance from the CRF. The drill entered the restricted region in 8.3% of the holes that were drilled.

There are various sources of error that are included in our measurements. One source of error comes from the voxel size of the CT image used to validate the system. These voxels measure 0.5 mm by 0.5 mm by 0.4 mm. Due to this size, it is impossible to be accurate in our validations to within 0.35 mm. In the case of the first experiment, many of the distances were within the width of one voxel length to the surface. Another source of error is due to the nature of the balsa wood. When ablating the wood, balsa fibers, unlike bone, tend to shred, leaving a rough surface on the balsa block. This shredding made it extremely difficult to differentiate between the balsa and air in the CT image at the edges. This problem was exacerbated by the closeness in intensity that air (intensity = −1024) and balsa (about −900) share in a CT. For this reason, there is an uncertainty in choosing the edge voxels that were used to determine the distance to the restricted region. Yet another source of error occurs during the tracking process. Part of this error is caused by inaccuracies in locating the probe tip during registration, causing registration error. The target registration error (TRE) observed during probe calibration was 0.4 mm. Additionally, error in calibrating the drill itself causes inaccuracies during its tracking. The TRE observed during the drill calibration was 0.45 mm. The time delay between entry of the drill into a restricted region and disablement and the inertia of the drill causing it to continue ablating after its power has been removed, contributes error.

### 5. CONCLUSION

A drill disablement system was successfully designed, created, and tested. To our knowledge, only Strauss et al.[3] have previously presented a similar system to prevent damage to anatomy during mastoidectomy. However, our study is the first to present a drill disablement system using MicronTracker and IGSTK. The system used in Strauss’ study exhibited a mean error of just over three millimeters, while our system exhibited a mean error of less than two millimeters.

Our system was used to resect a balsa block phantom with “restricted regions” defined inside to imitate patient anatomy. During the tests, the drill was consistently disabled as it neared the restricted regions inside the phantom. In Experiment 1, the drill was stopped, on average, 0.74 mm from the restricted region. The drill entered the restricted region for only.
5.3% of the area drilled, and only entered an average of 0.24 mm in these areas. These results are extremely promising and confirm that the drill disablement system could be used in a surgical environment. The drill was not quite as accurate during Experiment 2. However, when considering the error inherent in the system, the results were still accurate enough to encourage further development of the system.

The tests we conducted consisted of only one registration, and error in this registration transformation affects the entire test. Additionally, no obvious trend of decreasing accuracy as the drill moved away from the CRF could be observed. Further experimentation with the system is being conducted to analyze and improve the performance of the drill disablement system.

In conclusion, the drill disablement system shows promise, and its development could prove to be an additional safety feature provided for image-guided surgeries.

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